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Study of Two-Layer System Tin/$Ni_{0.905}W_{0.095}$ Adoptable for Creating Paramagnetic Substrates with Cubic Texture for 2G HTS Superconductors

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I. Introduction

Research in the field of high-temperature superconductors of the second generation (2G HTS) based on YBCO textured films is of particular interest because it opens up new perspectives for creating coated conductors, which could operate in high magnetic fields at temperature of liquid nitrogen (77.4 K). [1 – 6]. First off all this refers to the transfer of electric current over long distances (in particular from the NPP to the consumer), the creation of powerful magnetic fields, etc [7, 8]. As known the architecture of 2G HTS [9] with crucial current density above $j_c \sim 10^6$ A/cm^2 at liquid nitrogen temperature should consist of three main components [10 – 13]:

1. Metallic substrate (thin flexible tape mostly of Ni – W alloys with different compositions);
2. Buffer layer/layers (oxides, nitrides, in particular TiN as seed layer);
3. Quasi monocrystalline film of high temperature superconductor $YBa_2Cu_3O_{7-\delta}$ (Tc ~ 92 K [14]) with strongly reduced fraction of high angle grain boundaries.

Fabrication of high-j_c, biaxially aligned HTS films can be achieved due to epitaxial growth on rolling-assisted biaxially-textured substrates (RABiTS) [11, 15 - 18]. The texture (100)[100] of the metallic substrate is conferred to the superconductor by deposition of intermediate layers which serve as a chemical and a structural buffers [19]. The presence of a conductive layer acting as an electric shunt to prevent the effect of thermal destruction of superconductor in the case of over-current opens up prospects for use of titanium nitride as the main seed buffer layer in the complex architecture of 2G HTS [20 — 22].

Moreover metallic substrate must be in paramagnetic state at low temperatures to reduce losses during ac current transport [23 - 25]. The property of paramagnetism is provided by increasing the concentration of tungsten in the $Ni_{(1-x)}W_x$ alloy to $x \sim 0.095$ [26, 27]. However, it hinders the formation of cube texture (100)[100] due to decreasing of stacking fault energy E_s of cold-rolled alloy. The E_{sf} decreases with increasing the content of alloying element in the alloy [28].

The main aim of this work is to find new ways to control properties of paramagnetic substrates based on $Ni_{0.905}W_{0.095}$ alloy for the creating of high-temperature superconductors with high current-carrying capacity (2G HTS).

The following research program was implemented:

1. Experimental study of the effect of nitrogen pressure during titanium evaporation on the structural features of both components of the two-layer system TiN / $Ni_{0.905}W_{0.095}$.
2. Experimental study of the influence of TiN deposition time on the structural features of the components of the TiN / $Ni_{0.905}W_{0.095}$ system at the optimal value of nitrogen pressure.
3. Experimental study of the influence of TiN deposition geometry on the structural features of both components of the TiN / $Ni_{0.905}W_{0.095}$ system.

Development of new ways to control the structure and properties of materials based on paramagnetic Ni-W alloys with TiN coating.

II. Materials and Methods

Preparation of substrates was carried out according to the scheme which includes following steps [29, 30]: 1) synthesis of paramagnetic alloy $Ni_{0.905}W_{0.095}$; 2) thin-layer tape production; 3) high-temperature

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treatment of NiW tapes; 4) deposition of titanium nitride on the surface of NiW tape; 5) XRD analysis of obtained samples.

The initial materials for obtaining the Ni – W alloys were Ni and W powders with 99.98 – 99.99 % purity (by metallic impurities). The following methods were used for the purification from gaseous impurities (the main impurity is oxygen represented as nickel and tungsten oxides): 1) the heat treatment at temperatures ~850°C for purification of Ni powder; 2) for the refinement of W powder was applied the high-temperature treatment (1000 – 1200°C) in reducing Ar + 4 % H_2 gaseous mixture flow. The paramagnetic alloy was synthesized be means of powder metallurgy in deep vacuum (p ~ 10^{-6} Torr) at T = 1200°C during t = 4 hours.

Obtained ingots were rolled up to 50 – 100 μm at room temperatures to perform metallic tapes. The total degree of cold-rolling deformation was about 95%. The resulting operation during the tape production was high-temperature annealing at T = 1150°C during t = 2 hours.

Thin layers of titanium nitride (TiN) on the surface of Ni - 9.5 at% W tapes were obtained by the method of ion-plasma deposition[31]. Specific parameters of the TiN buffer layer deposition varied within the following ranges: negative substrate potential U = 50 – 300 V; arc current I = 80 A; temperature of substrate t_s ~ 450°C; nitrogen pressure in chamber p_N = 1.2 — 6.2 · 10^{-2} Torr; deposition time τ_{TiN} = 0 – 900 s.

XRD analysis (Cu Kα radiation) was carried out to solve the following tasks: determination of the phase composition of the system components both the substrate $Ni_{0.905}W_{0.095}$ and coating TiN; determination of lattice parameters; analysis of the texture of the substrate and the coating [31]; determination of the TiN coating thickness [32-34].

The method of determination the Tin-layer thickness is based on X-ray absorption. The intensity of the beam reflected from crystal plane (h k l) of a sample with the coating thickness h is as follows:

$$I_{hkl}(h) = I_{hkl}(0) \cdot \exp\left(-2h \cdot \mu_{TiN} / \cos(\theta)\right) \qquad (1)$$

I_{hkl} *(h)* – the intensity of the beam reflected from the substrate with coating;

I_{hkl} *(0)* – the intensity of the beam reflected from the substrate without coating;

h – coating layer thickness;

μ_{TiN} – the linear absorption coefficient of the coating material;

θ – the Bragg angle.

Equation (1) and mathematical modeling of the relative intensity of some X-ray interferences, in our case - the cubic plane (h 0 0) of the Ni - W substrate, makes it possible to determine the coating thickness h_{TiN} within accuracy of about 10%.

III. Results

In the present study the TiN coating was deposited on the front ("face") and the back ("shadow") side i. e out of line of sight of the cathode beam of the $Ni_{0.905}W_{0.095}$ substrates. Two series of experiments were carried out:

- TiN deposition at constant time t_{TiN} = 3 min in a wide range of pressures of nitrogen p_N = 1.2 – 6.2 · 10^{-2} Torr.
- The deposition of TiN at constant (optimal) N_2 pressure of nitrogen at different times τ_{TiN} = 1 – 3 min.

Fig. 1 and Fig. 2 present a set of diffraction patterns of the system TiN/$Ni_{0.905}W_{0.095}$ for the experimental series at different pressures for both face and shadow deposition geometries. There are two systems of diffraction lines, which belong to the FCC lattice of $Ni_{0.905}W_{0.095}$ alloy and TiN lattice of type NaCl. As the pressure of nitrogen growths, textures of the substrate and coating exhibit variations.

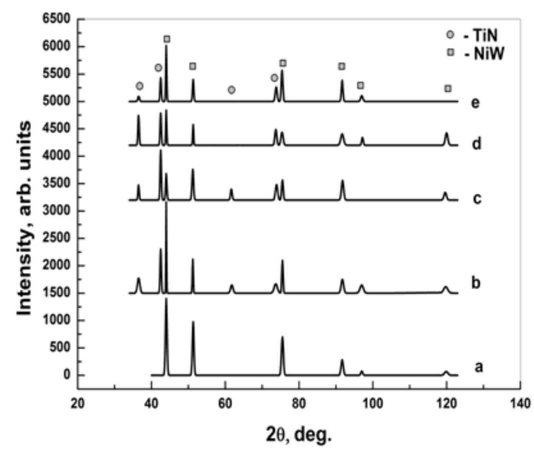

Fig. 1: Set of diffraction patterns of the system TiN / $Ni_{0.905}W_{0.095}$ for the experimental series at different pressures ("Shadow"): a) 0; b) 1.2, c) 1.8, d) 2.8, e) 3.8 ·10^{-2} Torr.

It is natural that the increase in p_N leads to growth of the intensity of the diffraction lines of TiN, but at the same time there is a tendency to redistribute the intensities of the diffraction lines in the subsystem of $Ni_{0.905}W_{0.095}$

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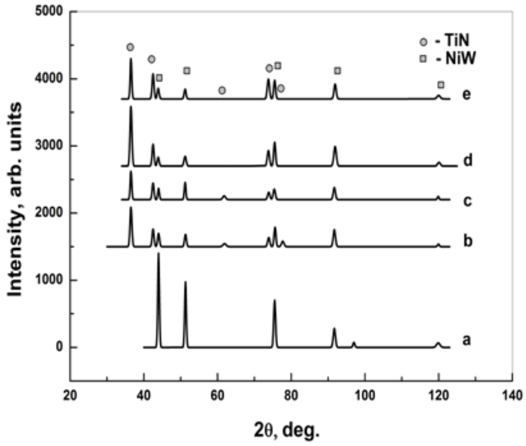

Fig. 2: Set of diffraction patterns of the system TiN / $Ni_{0.905}W_{0.095}$ for the experimental series at different pressures ("face"): a) 0; b) 1.2, c) 1.8, d) 2.8, e) 3.8 ×10 $^{-2}$ Torr.

The Fig. 3 clearly shows considerable growth of intensity from Ni-W "cubic" plane $I_{(200)}$ at $p_N \sim 1.8 \cdot 10^{-2}$ Torr, indicating the sharpening of cube texture of metallic component. The ratio of the cubic $I_{(200)}$ and diagonal $I_{(220)}$ diffraction lines intensity was chosen as a "texture parameter".

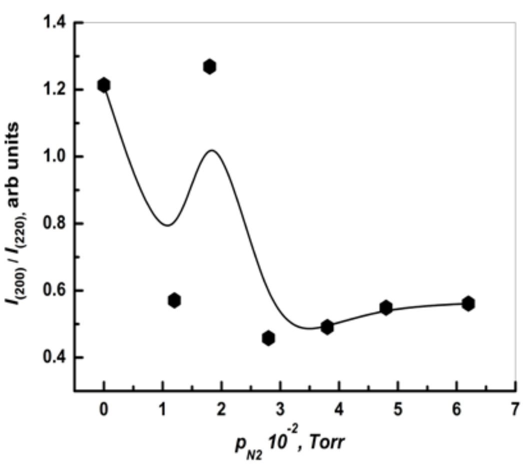

Fig. 3: Values of the ratio $I_{(200)}$ / $I_{(220)}$ of the $Ni_{0.905}W_{0.095}$ substrate after TiN deposition

The Fig. 4 shows dependences of TiN lattice constant a_{TiN} on the pressure of N_2 for different coating deposition geometries.

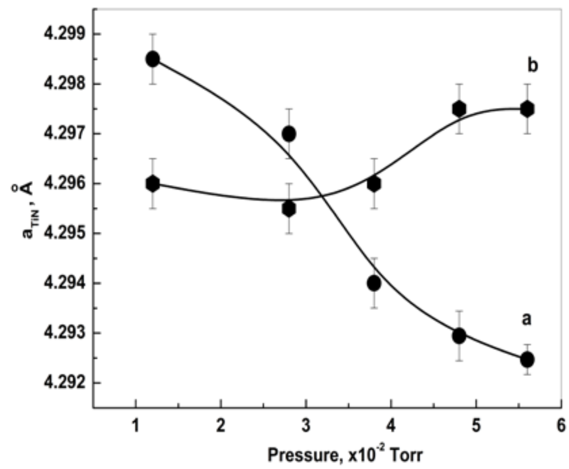

Fig. 4: The lattice parameters change of the TiN coating deposited onto the both sides of the $Ni_{0.905}W_{0.095}$ substrate at different pressures of nitrogen depending on the coating geometry: a) face; b) shadow.

As can be seen, in the case of "shadow" geometry, the curve a is weakly dependent on the p_N, while for "face" curve b decreases monotonically in the whole range of nitrogen pressures. Dynamics of variation of the TiN lattice parameter during crystalline phase formation in the coating can be associated with the change in the flux densities of titanium atoms and atoms of nitrogen depending on the coating geometry.

The above data (see. Fig. 1 - 4) give reason to believe that at pressures $p_N \sim 1.8 \cdot 10^{-2}$ Torr there are implemented the most favorable conditions for the formation of cube texture of substrate in TiN / $Ni_{0.905}W_{0.095}$ system. The evolution of diffraction pattern depending on the TiN deposition time at optimized $p_N = 1.8 \cdot 10^{-2}$ Torr = const is plotted in the Fig. 5.

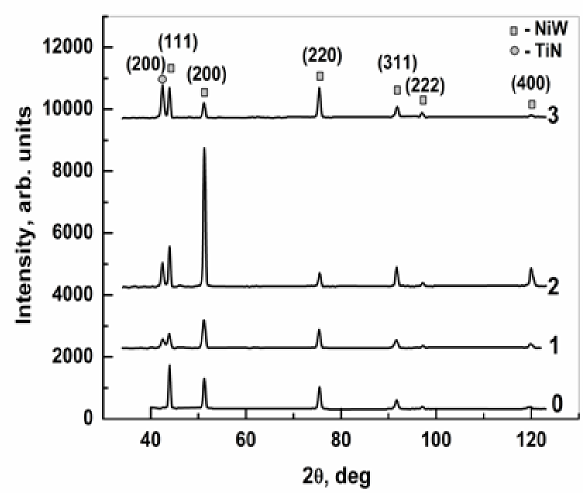

Fig. 5: XRD patterns of $Ni_{0.905}W_{0.095}$ alloy tapes with TiN coating ("Face") at $p_N = 1.8 \cdot 10^{-2}$ Torr in the range of 0 – 3 min (from the bottom up)

As the deposition time τTiN increases up to 2 min, in other words as the coating thickness growths, the relative intensity of (h 0 0) type diffraction lines increases, while the intensities of reflections from the diagonal (h k 0) and other FCC lattice planes decreases. Such behavior of the evolution of diffraction pattern indicates qualitatively substantial intensification of degree of the cubic texture component in $Ni_{0.905}W_{0.095}$ paramagnetic alloy tape. According to Fig. 6, that shows diffraction patterns of TiN / NiW systems obtained at different geometry of TiN deposition, mentioned above effect of texture enhancing is more apparent for the "face" coating geometry.

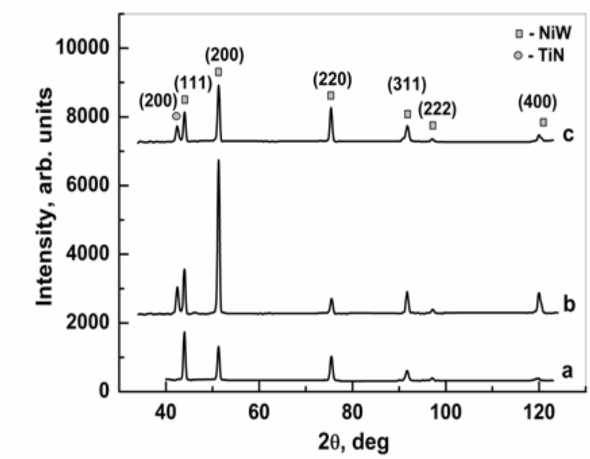

Fig. 6: XRD patterns of $Ni_{0.905}W_{0.095}$ alloy tapes with TiN coating ("Face") at $p_N = 1.8 \cdot 10^{-2}$ Torr in the range of 0 – 3 min (from the bottom up). XRD patterns of $Ni_{0.905}W_{0.095}$ alloy tapes with TiN coating obtained at optimized conditions at different coating geometry a) Original sample, b) Face, c) Shadow.

The Fig. 7 shows the dependency of texture parameter for $Ni_{0.905}W_{0.095}$ versus TiN coating deposition time.

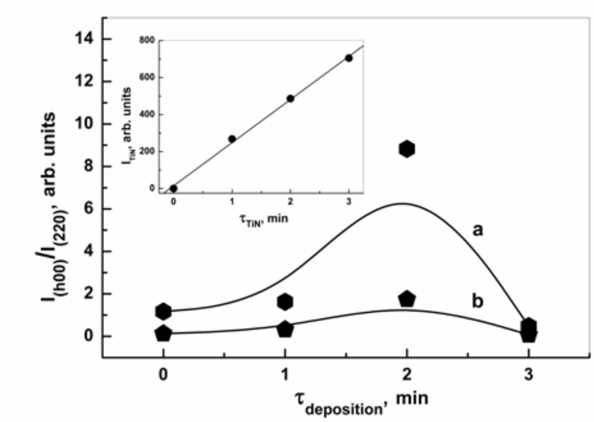

Fig. 7: Dependency of $I_{(h00)}$ / $I_{(220)}$ ratio from $Ni_{0.905}W_{0.095}$ substrate on deposition time. Inset: Dependency $I_{(200)}(\tau)$ for titanium nitride coating

As can be seen it exhibits strong maximum at τ_{TiN} = 2 min that corresponds to h_{TiN} ~1 μm. Process of cubic texture formation is also observed in the coating layer of TiN. This is proved by the presence of only $(200)_{TiN}$ diffraction line, which belong to cubic plane of the TiN lattice. The inset in the Fig 7 indicates that $I_{(200)}$ from TiN monotonically increases in the whole range of τ_{TiN}.

In order to determine fine variations of texture in the TiN / $Ni_{0.905}W_{0.095}$ system the algorithm of circular diagrams was used as a supplementation to the classical ways. This method is based on the construction and analysis of diagrams of the angular distribution of the intensity from crystallographic planes. In order to study the density of normals to (h k l) planes in various directions, a sample need to be rotated by angle ϕ about the normal to its surface.

As a criterion for the validity of the initial hypothesis regarding the realization of perfect cubic texture was chosen the known statistical method χ^2. To calculate it n = 23 degrees of freedom were considered. Of course in the case of forming an ideal cubic texture, the value of "Chi - square" tends to be zero.

By way of illustration the Fig. 8 shows circular diagram from plane of type (h 0 0) for TiN coating at τ = 2 min, where texture effects at which texture effects are most pronounced. The Fig. 9 shows circular diagrams from (2 0 0) plane related to $Ni_{0.905}W_{0.095}$ subsystem before (Fig. 9a) and after coating (Fig. 9b) at optimized parameters:

$$h_{TiN} = 1\ \mu m,\ p_N = 1.8 \cdot 10^{-2}\ \text{Torr}.$$

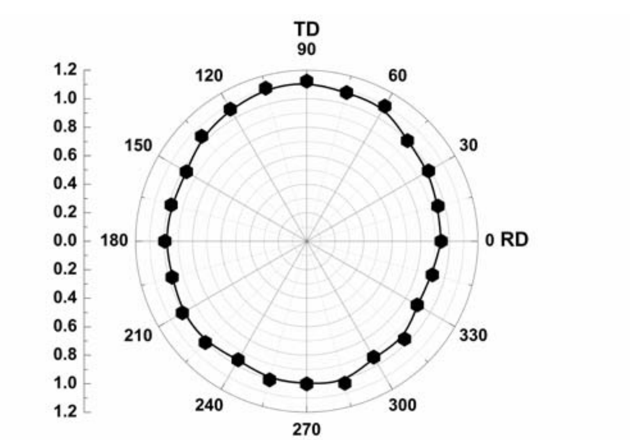

Fig. 8: Circular diagram of (2 0 0) plane for TiN coating layer

It is worth to mention that for crystals belonging to cubic symmetry, the polar absorption tensor does not depend on the direction. Thus, any change in the intensity of the diffracted beam can be solely attributed to the processes of texture formation occurring in a two-layer system "substrate – coating".

One can see from the graphs above that the deposition of the TiN coating leads to the improvement of the cubic texture ($\chi_{tape} = 0.11 \rightarrow \chi_{coated} = 0.07$) in the metal component (Ni-W) of the two-layer system TiN / $Ni_{0.905}W_{0.095}$ as well as to formation of strong texture in coating layer ($\chi_{TiN} = 0.005$).

IV. Disscussoion

The subject of discussion in this paper is a set of observed effects related to the peculiarities of cubic texture formation in the thin-film system TiN / $Ni_{0.905}W_{0.095}$ (see Fig. 3 – 9):

1. Qualitative changes in the variation of the crystal lattice parameter dependencies of titanium nitride on the nitrogen pressure by varying the “geometry” of deposition during the experiment.
2. The formation of rather strong cubic texture in metallic layer of the thin-layer system TiN/ $Ni_{0.905}W_{0.095}$.
3. The formation of quasi mono crystalline structure of TiN buffer layer in the system TiN / $Ni_{0.905}W_{0.095}$.

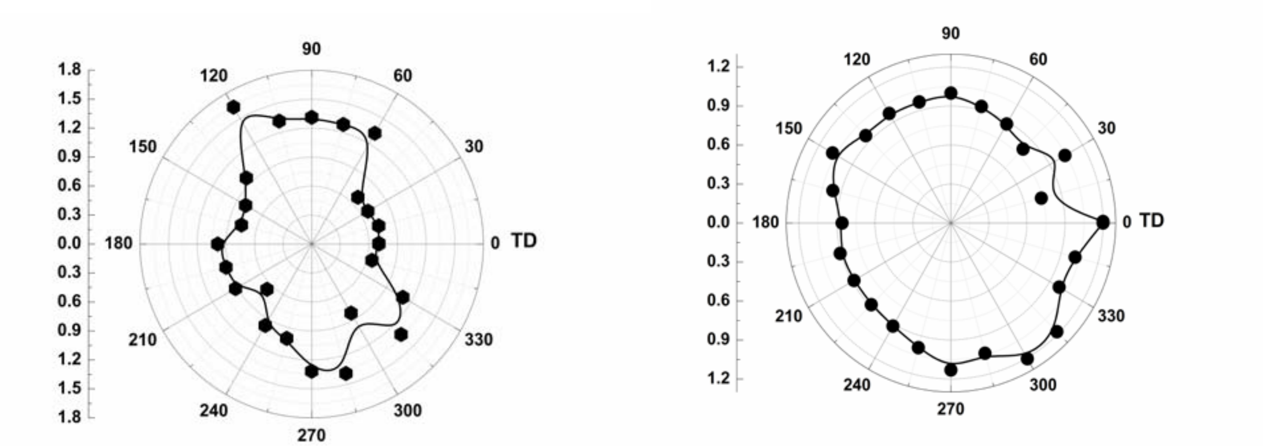

Fig. 9: Circular diagram of (2 0 0) plane from a) original tape based on alloy $Ni_{0.905}W_{0.095}$ and b) subsystem

The identified differences in the dependences of the lattice parameters of titanium nitride may be caused by differences in the mechanisms and kinetics of the phase formation of TiN titanium nitride during deposition on different sides of the Ni-W tape. Dependence on the “front” side reflects the increase in the proportion of atoms with low atomic radius. On the “shadow” side the dependence reflects the mechanical reduction of titanium ion flux density due to deposition on the opposite side of the substrate. It is possible that the order of the reaction of the interaction of Ti and N ions may change.

The set of data presented in the figures 5 - 7 clearly indicates the processes of texture formation in substrate based on the paramagnetic alloy $Ni_{0.905}W_{0.095}$.under influence of TiN layer. This is clearly supported by the change of shape of intensity distribution from $(200)_{NiW}$ crystal plane as shown in the Fig. 9.

The effect of an anomalous increase in the degree of cubic texture of the substrate, as well as the formation of a biaxial texture in the coating layer, is obviously associated with the process of reorientation of crystallites of both components of the TiN / $Ni_{0.905}W_{0.095}$ system under the influence of interfacial stresses arising at the interface of materials with different values of the lattice parameters.

V. Conclusion

Ways to control the architecture of two-layer system TiN / $Ni_{0.905}W_{0.095}$ based on the change of nitrogen pressure during titanium evaporation, deposition time, and coating geometry were developed.

The conditions for creating two-layer “substrate – coating” compositions are optimized, which provide the possibility of obtaining strong cubic texture in the TiN coating layer deposited on the surface of the tape based on paramagnetic alloy $Ni_{0.905}W_{0.095}$.

The main result of the work is the experimental detection of the effect of correlated formation of a cubic texture in both components of the two-layer system TiN / $Ni_{0.905}W_{0.095}$, which should provide a significant increase in critical current density of 2G HTS coated conductors.

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